

The effect of three cognitive variables on students' understanding of the particulate nature of matter and its changes of state

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The effect of three cognitive variables on students’ understanding of the particulate nature of matter and its changes of state

Abstract

In this study, students’ understanding of the structure of matter and its changes of state, such as, melting, evaporation, boiling and condensation was investigated in relation to three cognitive variables: logical thinking, field-dependence/field-independence and convergence/divergence dimension. The study took place in Greece with the participation of 329 ninth-grade junior high school pupils (age 14-15). A stepwise multiple regression analysis revealed that all of the above mentioned cognitive variables were statistically significant predictors of the students’ achievement. Among the three predictors, logical thinking was found to be the most dominant one. In addition, students’ understanding of the structure of matter, along with the cognitive variables, were shown to have an effect on their understanding the changes of states and on their competence to interpret these physical changes. Path analyses were implemented to depict these effects. Moreover, a theoretical analysis is provided that associates logical thinking and cognitive styles with the nature of mental tasks involved when learning the material concerning the particulate nature of matter and its changes of state. Implications for science education are also discussed.

Keywords

Particulate structure of matter, changes of state, logical thinking, cognitive styles, field-dependence/field-independence, convergence/divergence thinking.

Introduction

This paper contributes to understanding the students’ difficulties related to the structure of matter and its changes of state, by investigating the role of some cognitive variables. The structure of the present report has as following: First, in the Introduction section, a lucid review is presented in order to highlight the extent and the diversity of students’ difficulties, and in addition to show the limitations and the partial success of the teaching interventions reported. Second, the section on cognitive variables reports on the three cognitive variables, which have been related to science education research. In the third section, the Rationale of the present study is developed and the research hypotheses are stated.

Next follow the sections of Method, Additional Research Directions, the Statistical Analysis and Results. In the Interpretation of results and Discussion section, a theoretical analysis is provided that associates the cognitive variables with the nature of mental tasks involved when learning about structure of matter and its changes of state, while in the final section implications for science education are discussed.

A great deal of research has been conducted in order to shed light on students' ideas related to the structure of matter and its changes of state. For the last decades, all relevant papers have reported conceptual understanding difficulties in this field.

With regard to gas state, Novick and Nussbaum (1978), after clinically interviewing eighth grade pupils in Israel, found that "a significant portion of the sample failed to internalize important aspects of the particle model". As a matter of fact, although it was only the minority of the subjects that adopted a continuous model of matter, many of those pupils who had accepted the particle model showed that they had a problem in conceiving the notion of "empty space" among particles, especially in the gas state. Therefore, they erroneously responded by filling the space among gas- particles with other particles, such as air or dust. Moreover, the intrinsic motion of gas particles was also found to be a difficult concept. That was attributed to various causes, e.g. to low gravity or to the air moving the particles. In a later cross-age study, Novick and Nussbaum (1981) used a paper-and-pencil instrument in order to penetrate pupils' understanding regarding some aspects of the particle model associated mainly with gases. Their study involved subjects over a wide range of age, from fifth-grade pupils to university sophomores, and they found again a different internalization of the various aspects of the particle model. It is important that only 20% of the elementary-school pupils and the high-school juniors as well, answered that there is no material between the particles. The corresponding percentage at senior high school and university level increased only to 37%, indicating that the difficulty in conceiving the vacuum between particles is still persistent in higher education levels.

Another cross-age study investigating students' preconceptions of the nature of gases was conducted by Benson, Wittrock and Baur (1993), who reported a relatively limited number of misconceptions inferred from students' drawings. These misconceptions were found to be one or more of the following: (a) air is a continuous substance, (b) gas behavior is similar to liquid behavior and (c) there is relatively little space between gas particles. The authors underlined "the number of drawings that gave evidence of particulate views ranged from 8% for grades 2-4 to 85% for university chemistry students. However, 33% of the

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university students' drawings showed highly packed particles and only 37% showed particles in an approximately correct geometrical distribution".

Additional evidence for the inherent difficulty in conceiving the structure of the gas state was reported by Stavy (1998), who argued that students do not develop spontaneously a general idea of *gas* prior to their formal introduction on this matter. Definitions for the term *gas* by means of the particulate theory of matter were given only by grade-8 and grade-9 students who had been taught this theory one or two years earlier, when they were in the seventh grade. These definitions included one or more of the following points: distance between particles, motion of particles, arrangement of particles and attraction forces between particles. None of the seventh-grade students gave a definition at this level. In the light of the above findings, one could conclude that a considerable time period might be required for the assimilation of these ideas.

With regard to solid and liquid states, students' conceptions were found to be similar to those of gases: continuous or particulate model of matter, space between particles, particle motion, attractions between particles (Renstrom et al., 1990; Lee et al., 1993; Johnson, 1998a). The adoption of the particle concept is not always in accordance with the scientific view. Research has shown that students consider molecules as being in a continuous substance like "blueberries in a muffin" (Lee et al., 1993). According to this view, "particles are additional to the substance" (Johnson, 1998a).

An additional and interesting point is that, students have a great deal of difficulty to understand that the properties of the states of matter are due to the collective behavior of particles. They often regard a particle or a molecule as a little quantity of a substance having all the macroscopic properties of the substance. That is, ice molecules or particles are regarded as frozen or 'solid molecules, water molecules as 'liquid molecules', and so forth (Lee et al., 1993; Johnson, 1998a). Furthermore, molecules are described to undergo "the same changes as the visible changes in the substances. Thus, molecules start to move when ice melts into water, molecules of water are heated up and make water boil, or molecules expand, contract, melt, evaporate, condense, and so forth" (Lee et al., 1993).

Significant conceptual difficulties are reflected in the way that students make a distinction between states, which are not always clear or complete. Secondary students' misconceptions about liquids are due to the fact that they consider liquids to be merely in an intermediate state between solids and gases. In this context, students overestimate the molecular spacing in liquids. Furthermore, many of them believed that although particles in gas and liquid state were in constant motion, there was no particle movement in solid state

(Dow et al., 1978). In another study, molecular spacing in gases has been found underestimated, while the particle motion has been ignored by the majority of the students (Pereira & Pestana, 1991). Misconceptions have been also reported in relation to particle size of a substance that is thought to vary in different states (Dow et al., 1978; Griffiths & Preston, 1989; Pereira & Pestana, 1991).

In an attempt to further investigate the various students' conceptions related to the nature of matter and organize them into conceptual categories, a longitudinal study with secondary English pupils (ages 11-14) carried out by Johnson (1998a), led to the formation of distinct models for students' classification on the strength of their particle thinking. These distinct models are defined below:

(1) *Model X*: Continuous substance. Particle ideas have no meaning. (2) *Model A*: Particles *in* the continuous substance. The particles are additional to the substance. (3) *Model B*: Particles *are* the substance, but with *macroscopic* character. There is nothing between the particles. Individual particles are seen as being of the same quality as the macroscopic sample - literally small bits of it. (4) *Model C*: Particles *are* the substance. The properties of a state are seen as *collective* properties of the particles.

In addition to the above, there are intermediate models. It was also suggested that these models might represent stages through which, students' ideas evolve towards the science model (Johnson, 1998a).

As far as the changes of state are concerned, Osborne and Cosgrove (1983) investigated students' perceptions by interviewing forty-three school pupils ranging in age from eight to seventeen years. The findings were consolidated by means of a paper-pencil survey technique. Regarding melting, in a question asking what is happening to a block of ice melting on a teaspoon, only eight out of forty-three pupils answered in terms of the particulate structure of matter. These pupils responded that the heat made the particles move farther apart. It appears that the pupils used a general model, which relates volume and temperature for many substances. Other common answers were: (a) ice melted because it was above its melting temperature and (b) it just melted and changed into water. Regarding boiling, in the same study, and in a question asking what the bubbles in boiling water were made of, only five out of forty-three pupils (ranging from thirteen to seventeen years old) answered that the bubbles consisted of steam. Common misconceptions in pupils' views were: (a) the bubbles were made of heat, (b) the bubbles were made of air and (c) the bubbles were oxygen and hydrogen. View (b) was the most frequent one, while view (c) was held by some older pupils. Findings similar to (b) and (c) were also reported in a study of Bonder (1991).

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Bar and Travis (1991) made an effort to “widen the conclusions of Osborne and Cosgrove concerning the application of abstract concepts by pointing out the universality of their results in the course of extending them to another country” (p. 364). According to Bar and Travis, “many children know that water changes into gas by the process of boiling, but they do not understand that the same change can occur by evaporation” (p. 371). Thus, one of their main new findings was that “the understanding of boiling precedes the understanding of evaporation”.

During his longitudinal study, Johnson (1998b) explored, among others, the development of children’s conceptions about boiling water. He ascertained that by the end of the study, half of the pupils interviewed had reached the idea of the bubbles being “water as a gas” and that this progress was facilitated by particle ideas. Having accepted these basic ideas, pupils are able to develop a meaningful conception of what a gas is. Johnson considers that “the particle model must be seen as a mean of first establishing the possibility of a sample of substance being in a gas state” (p. 582).

Regarding the nature of steam above boiling water, in the study of Osborne and Cosgrove (1983), the most common answers of pupils were: “smoke”, “water”, “a kind like water” or “water in a different form”. Many children considered that steam had changed into air while some others thought that the air and the steam were the same. Also, there were pupils who thought that the steam was made of oxygen and hydrogen. Expectedly, some of these answers are similar to those describing the bubbles in boiling water. The same authors, in order to further investigate children’s views about condensation from steam, placed a saucer (plate) above boiling water and then asked children about the water that had been formed on the saucer’s surface. The questions were: “What is this on the saucer?” and “What has happened here?” Only seven out of forty-three pupils responded in such a way that involved a particle model. The most characteristic of pupils’ responses were: (a) it has all gone sweaty, (b) the steam makes the plate wet, (c) the steam changes back into water, (d) the hydrogen and oxygen in the steam recombine to form water and (e) the steam has cooled and the water molecules have moved closer together. A noticeable fact is that although many children used the term “condensation” to describe what had happened on the saucer, the majority of them showed little real understanding of this term.

In order to elicit pupils’ views about evaporation, in the same study, the authors turned the saucer upside-down so that the water from the condensation of the steam to be on the upper side. After a while the water had evaporated. Pupils were asked what had happened to the water. Although many of them replied using the word “evaporation”, again only few

showed to have a scientifically deeper understanding of what this term means. The most characteristic pupils' responses were the following: (a) it has gone into the plate; (b) it has just gone...it has dried up; (c) it goes into the air and comes back as rain and (d) it changes into air. Among the pupils who gave the answer (c), only eight included particles or molecules in their explanations.

Pupils' ideas on evaporation has been also investigated by Bar and Galili (1994), who found that pupils' conceptual change on evaporation is correlated with pupils' cognitive development, their conception of the conservation of matter and the adoption of an abstract model of air. Johnson (1998c) has exemplified that there is a high consistency between pupils' responses to phenomena, such as evaporation, condensation and boiling, and the understanding of the nature of the gas state. The sound understanding of the nature of the gas state in terms of the particle theory of matter constitutes an underlying background for the understanding of all the above-mentioned changes of state. Particularly, for evaporation and condensation, Johnson (1998c) has stated that until one understands them both, "it could be argued that one really understands neither".

Stavy (1990a) explored pupils' conceptions regarding conservation of matter during evaporation or sublimation. In this study, pupils appeared to believe that "gas has no weight or that gas is lighter than the same material in its liquid or solid state". Furthermore, according to Stavy (1990b), "students believe that a molten material weights less than the same material in its solid form and that gas weights less than the same substance in its liquid or solid form". Similarly, Lee et al. (1993) found that students were confused about conservation of matter during evaporation, boiling and condensation, as all these changes of state involve invisible gases. "Since a substance becomes invisible during evaporation, some students thought that the substance disappears and ceases to exist". To a lesser extent, though, students were also found to have been "confused about the conservation of matter during melting and freezing" as they considered that "ice is heavier than water" or that "ice has more stuff in than water". Finally, Hatzinikita and Koulaidis (1997) exploring both the qualitative and quantitative dimensions of pupils' ideas relevant to conservation of matter during evaporation, boiling and condensation found that qualitative understanding precedes quantitative.

In the light of various findings, such as those mentioned above, teaching interventions have been conducted in order to promote students' conceptual understanding. Lee et al. (1993) studied the performance of two sixth-grade groups of pupils that had been taught the same science course concerning the nature of matter and its physical changes. Any valuable information about conceptual barriers that had been acquired from the teaching process in the

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first group (1st year) was used to improve the teaching intervention in the second one (2nd year). The study showed that the pupils of the second group performed better than those of the first one. Conceptual and understanding difficulties in the second group were overcome to a certain extent; however, by no means were they eradicated. Similarly, in an intervention study (Author 3 et al., 2005) taken place in a Greek school in the fifth-grade, pupils in the experimental group where particle ideas were incorporated in the teaching scheme, seemed to have developed a better understanding of phenomena, such as, changes of state and mixing compared to their peers in the control group. The results are promising and suggest that there might be room for improvement.

In order to contribute to a further clarification of pupils' particle ideas and to facilitate their better understanding regarding the changes of state, Author 3 et al. (2007) applied thoroughly designed computer simulations in a teaching intervention and compared the results to those of a corresponding intervention without the use of the software. In both, control and experimental interventions, the concepts of the particle theory of matter were implemented. The study showed that computer simulations seem to facilitate understanding of particle ideas and physical changes, such as, melting and evaporation. However, there were again a considerable number of pupils who did not reach the desired level of understanding.

In another study, Tsai (1999) examined the effectiveness of an analogy activity specially designed to overcome misconceptions of eighth-grade Taiwanese pupils about the microscopic views of phase change. The control group was instructed through traditional teaching and the results indicated that although the pupils of both groups improved their performance in an immediate post-test, the retention was higher in the experimental group. However, significant difficulties were not overcome, even though an improvement was demonstrated.

Costu et al. (2007) attempted to facilitate students' conceptual change on boiling by implementing appropriately designed teaching activities. The authors worked with fifty-two university students enrolled in introductory chemistry courses. The results showed that the teaching strategy followed "was an effective means of reducing the number of alternative conceptions students held about the boiling concept" (p. 531). However, it was found that "some students maintained their alternative conceptions throughout the study" (p.533), for example, although "the students' belief that bubbles in boiling water contain air decreased from pre-test (27%) to post-test (23%)", finally this belief increased considerably (47%) in a retention post-test.

It is worth mentioning here that a presupposition that might make the topic easier is basic knowledge of kinetic theory. However, in the related literature there is no explicit reference to *kinetic theory*, but some elements are incorporated in the particle theory of matter and specifically in the part that deals with gasses.

By all accounts, the findings from teaching interventions reinforce the evidence that despite the progress that could be achieved by means of appropriate teaching methods, pupils' misunderstandings of the particle nature and the physical changes of matter seem to persist to a considerable extent. Thus, the question raised is what hinders pupils' understanding. Researches investigating this question were focused on difficulties originated from the material itself and suggest some presuppositions for understanding the particle nature and the physical changes of matter. For instance, Johnson (1998a, b, c,) proposed more elementary dimensions, as presuppositions, namely the particulate and collective dimensions, which were elaborated in the introduction section and have also been examined in the present research.

However, the partially successful teaching and the fact that a number of students can approach the science view, while many others are far behind, suggest that the individual differences, which are ignored in the related research might be worth examining. Ergo, it could be a potential area of investigations. Considering the above, the present work attempts to shed light on students' misunderstandings in the field of the particulate nature of matter as well as its changes of state by taking into account their individual differences. Cognitive variables, such as field dependence/field independence, convergence/divergence dimension and logical thinking (for developmental level) are implemented in a quantitative research to explain the variation of students' *understanding* in this specific domain. The significance and the role of the above mentioned three cognitive variables in science education research are presented and elaborated in the following part.

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Cognitive variables

a. Field dependence/independence (FDI)

Field dependence/independence (FDI) is a cognitive style associated with one's ability to disembed relevant information from complex and potentially confusing contexts (Witkin et al., 1977). Long-lasting investigation on the matter showed that some people are dominated by any strong frame of reference or pattern in a stimulus field to such an *extent* that they have trouble in perceiving elements that cut across the pattern. Those who can insufficiently separate an item from its context and who readily accept the dominating field or context are

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characterized as field-dependent, while those who can easily “break up” an organized perceptual field and separate readily an item from its context are characterized as field-independent (Witkin & Goodenough, 1981). However, the two qualities are not regarded as two distinct categories. On the contrary, there is a continuum between them and those of an intermediate ability are classed as field-intermediate. The FDI cognitive style is also connected with one’s ability to efficiently separate the *signal* from the *noise*. As *signal* could be considered what matters or the significant information, while as *noise* the incidental, peripheral and irrelevant information (Johnstone & Al-Naeme, 1991). Field dependence/independence has been related to the information processing models as a moderator variable. Field-dependent subjects appear to possess lower information processing ability, since part of their capacity is being used to process irrelevant information (Johnstone & Al-Naeme, 1991; Tsaparlis & Agelopoulos, 2001; Author 2, 2006).

Disembedding ability has been found to be related to structural ability in such a way that field-independent individuals are more able to deal with ill-structured tasks than field-dependent individuals (Goodenough & Karp, 1961; Witkin et al., 1962). In general, evidence supports supremacy of field-independent learners regarding cognitive analysis and restructuring skills in comparison with field-dependent learners (Witkin & Goodenough, 1981). Furthermore, academic performance in various disciplines such as language, mathematics, natural sciences, social sciences, art and computer sciences was examined in relation to FDI, leading to the conclusion that “in general field-independent subjects perform better than field-dependent subjects, whether assessment is of specific disciplines or across the board” (Tinajero & Paramo, 1998). Following, many research findings were in accordance with the above conclusion (Bahar & Hansell, 2000; Danili & Reid, 2004; Kang et al., 2005; Tsaparlis, 2005; Danili & Reid, 2006).

b. Convergence / divergence (CD)

Convergence/divergence is another cognitive style that was introduced because of the growing feeling that typical intelligence tests did not measure all aspects of intelligence. Intelligence tests are thought to favor those who find the one conventionally accepted solution to a problem when this solution is clearly obtainable from the information available. On the other hand, those who are able to respond successively in problems requiring the generation of several equally acceptable solutions obtain low scores in intelligence tests. The first are described as convergers, while the second as divergers. Thus, convergent is thought to be someone who focuses down-converges-on the one right answer in order to find the solution of

a problem, while divergent is one who is capable to generate responses, to invent new ones, to explore and expand ideas, and in a word, to diverge. Convergences use close reasoning, while divergers show fluency and flexibility (Child & Smithers, 1973).

Getzels & Jackson (1962) distinguished intelligence from creativity. In the same direction, Hudson (1966, 1968) tried to measure science/arts aptitude by devising different types of tests and he was led to the conclusion that a converger "is substantially better at the intelligent tests than he is at the open-ended tests; the diverger is the reverse" (Hudson, 1966). Although many researchers adopted the equation of divergent thinking with creativity and convergent thinking with intelligence, there were others that supported different results (Nuttall, 1972; Bennett, 1973; Runco, 1986; Fryer, 1996).

In a Hudson's (1966) research it was found that most of the physical scientists of his sample were convergers while most of the art specialists were divergers. However, biology, geography, economics, and general arts were found to have attracted "convergences and divergers in roughly equal proportions" (Hudson, 1966). Regarding biology, Orton (1992) and Bahar's (1999) findings are consistent with Hudson's finding. Other researches dealing with the matter of the relationship between convergence/divergence cognitive style and performance in science present interesting results: Divergent students were found to have scored higher than convergent students in mini projects in chemistry (Al-Naeme, 1991). Furthermore, divergers are reported to have achieved better results than convergers at the end of a university science course, despite the fact that the majority of the students were convergers (Field & Poole, 1970). Hudson (1966) noted on the matter that the convergers tended to choose the sciences, but the divergers who did choose the sciences performed very well. Johnstone & Al-Naeme (1995) reported that among the secondary pupils who participated in mini-projects (problem solving at the bench), the curious, field-independent and divergent pupils were those who did best. Danili and Reid (2006) explored high school pupils' performance in chemistry in relation to different assessment formats. The results showed that the convergence/divergence cognitive style was correlated with pupils' performance. The authors suggested that short answer or open-ended questions favored divergent style pupils.

Moreover, research concerning high ability studies has suggested that creativity is a consistent outcome of divergent thinking ability. Measures of divergent thinking have been correlated with creative output in many different domains studied, such as, visual art, literature, music, science, engineering, and business ventures (Guastello, Bzdawaka, Guastello, & Rieke, 1992). Nevertheless, it is important to emphasize that the conceptual

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differentiation of convergent vs divergent thinking does not correspond to two contradictory opposites. They are not mutually exclusive, but they are rather complementary and for science education mixed types are required. For example, in a complex problem-solving process, primarily, divergent abilities are necessary and later on in the process, convergent thinking is required for decision-making and conclusion (Facaoaru, 1985; Heller, 2007).

c. Logical thinking (LTh)

Logical thinking is a Piagetian concept and refers to the ability of the subject to use concrete- and formal-operational reasoning (Lawson, 1978, 1985, 1993). Concrete- and formal-operational reasoning are needed for understanding of concrete- and formal-operational concepts respectively. “Concrete-operational concepts are concepts whose meaning can be developed from first hand experience with objects or events” while “formal operational concepts are concepts whose meaning is derived through position within a postulatory-deductive system”. “The term *postulatory-deductive* refers to the theoretical models (systems) of science. Meaning is given to these concepts not through senses but through imagination or through their logical relationship with the system” (Lawson, 1975).

Logical thinking was assessed by the Lawson test, a pencil-paper test of formal reasoning (Lawson, 1978). The items included in the test require the following reasoning modes: Proportional, combinational and probabilistic reasoning as well as reasoning related to the isolation and control of variables, conservation of weight and displaced volume. The first four modes correspond to formal operational-reasoning, while the last two modes correspond to late concrete- and early formal-operational reasoning (Lawson, 1978). There are a lot of studies reporting that logical thinking plays a major role in students’ performance in science. Some of them are of the following researchers: Sayre & Ball (1975), Lawson (1982), Chiappeta & Russell (1982), Chandran et al. (1987), Lawson & Thomson (1988), Zeitoun (1989), Niaz (1996), BouJaoude et al. (2004), Author 2 et al. (2005). It is worth mentioning that in Lawson’s (1982) study, students’ formal reasoning has been correlated not only with achievement in science and mathematics, but with social studies achievement as well.

Rationale - Research hypotheses

All research work on understanding the particle nature and the physical changes of matter has been mainly exploratory and descriptive by revealing students’ errors and

misconceptions or difficulties without, however, providing explanations about their origin or correlating them with independent variables. An exception is Johnson's work (1998a, b, c,) where, the *particulate* and the *collective* dimensions were proposed as underlying presuppositions for understanding the particle nature of matter. On the other hand, teaching interventions showed that the difficulties still persist. Ergo, it is reasonable to hypothesize that the area of investigation could fruitfully expand to individual differences and specifically to cognitive variables, which have been proved predictive elsewhere in science education research.

When it comes to investigation of students' achievement in science with regard to cognitive variables, there are only a few such cognitive variables that are taken into account according to the literature, and these are the following: logical thinking (formal reasoning ability), field-dependence/independence, convergence/divergence, prior knowledge, *M*-capacity and working memory capacity (Lawson, 1983; Chandran et al., 1987; Zeitoun, 1989; Johnstone & Al-Naeme, 1995; Niaz, 1996; Tsaparlis & Angelopoulos, 2000; Kang et al., 2005).

From the above variables, the prior knowledge and the information processing capacity were not examined in this investigation. The influence of prior knowledge on students' achievement is investigated when a teaching intervention is conducted and the comparison of pre and post results is desired, which is not the case in this study. Moreover, *M*-capacity and working memory capacity are associated with information processing and thus, they were found to be mainly correlated with students' ability in solving problems (Niaz, 1996; Author 2 et al., 2005). However, in cognitive tasks with not a high processing demand these variables might be expected not to play a major role (Lawson, 1983; Tsaparlis & Angelopoulos, 2000). Regarding the present research, the instrument, which was implemented for assessing students' understanding of science concepts and phenomena, did not require simultaneous processing of a large number of *chunks* (Simon, 1974), that is, a large number of specific facts or concepts. Therefore, students' working memory capacity (or *M*-capacity) was not expected to constrain their performance. Consequently, the above variables were not included in this study. However, it is worth mentioning that the information-processing capacity might have shown positive correlation coefficients with achievements, because it is correlated with the general IQ.

The other three cognitive variables, logical thinking, field-dependence/independence and convergence/divergence, seem to play a significant role in a wide range of tasks and they affect students' performance in science according to the evidences mentioned in the previous

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section. Thus, these cognitive variables might also be potential predictors of students' understanding the particulate nature of matter and its physical changes, such as melting, evaporation, boiling and condensation. Moreover, aspects of the cognitive skills that are behind the psychometric measurements of these variables could support their choice. For instance, linguistic ability or disembedding ability might relate to the nature of mental tasks involved when learning/teaching this specific domain material. These aspects are elaborated *post factum*, in the discussion section, where a theoretical explanation of the findings is provided.

Considering the above, the main hypothesis in this research study is that students' understanding of the particulate nature of matter and its changes of state are affected by the following three cognitive variables: (a) logical thinking, (b) field-dependence/independence and (c) convergence/divergence. In addition, the following hypothesis is tested: students' understanding of the structure of matter along with the cognitive variables have an effect on their understanding and explaining the changes of states. This second hypothesis along with some additional research directions is further elaborated in a following section.

Method

Subjects

This study was conducted with the participation of 329 ninth-grade junior high school Greek pupils (age 14-15), 160 of which were male and 169 female. The sample consisted of all the pupils of 18 classes each of which belonged to a different junior high school. All of the schools are located in the prefecture of Fthiotida, in central Greece; 7 of them are in the capital (Lamia) while the other 11 are dispersed at the municipalities of the prefecture. All of the junior high schools of the capital and almost half of the remaining junior high schools in the prefecture took part in the research. Pupils of different socioeconomic status and living conditions comprised the sample.

Instruments

Data were collected during one school year through paper-and-pencil tests. The instruments used were the following:

Field dependence/independence (FDI): FDI ability of the subjects was assessed by a version of the Wittkin et al. (1971) Group Embedded Figures Test (GEFT). This is a timed test (20

min) in which the subject's task was to locate and outline simple figures concealed in complex ones. In this study a Cronbach's alpha reliability coefficient of 0.84 was obtained.

Convergence/divergence (CD): A six-item test was used to measure the extent of divergency of the subjects. Each item substantially constituted a mini test from itself. Briefly, the six mini-tests asked students to do the following: (test-1) to generate words of the same or similar meaning to those given, (test-2) to construct as many sentences as possible using four given specific words in each sentence, the words to be used in the form as given, (test-3) to draw up to five different figures relevant to the idea of a given word, (test-4) to write as many things as possible that have a common trait, e.g. things that are round or that are round more often than any other shape, (test-5) to think and write as many words as they could that begin with one given letter and end with another given letter, (test-6) to list all of the ideas they could about a given topic, whether or not it seemed important to them. The whole test had been widely used by Bahar (1999). It had also been used by Danili and Reid (2006) for measuring divergency of a Greek student sample. For the measures in this study, the Cronbach's alpha reliability coefficient of the instrument is 0.76.

Logical thinking (LTh): Pupils' logical thinking abilities were measured using the Lawson paper-and-pencil test of formal reasoning (Lawson, 1978). The test consists of 15 items involving the following: conservation of weight (1 item), displaced volume (1 item), control of variables (4 items), proportional reasoning (4 items), combinational reasoning (2 items) and probabilistic reasoning (3 items). The students had to justify their answers. A Cronbach's alpha reliability coefficient of 0.79 was obtained for the present sample.

Pupils' achievement, concerning their understanding of the particulate nature of matter and its changes of state:

The instrument was synthesized by selected items/questions, which have been used to assess students' knowledge on this specific domain in a number of research studies (Johnson, 1998a, b, c; Osborne, & Cosgrove, 1983; Author 3, Author 2 *et al.*, 2008). In particular, it was especially based on an extended and more elaborated version of the instrument used by Author 3, Author 2 *et al.*, (2008).

The test consists of 3 parts covering the following topics: the particulate nature of matter (first part), the properties of a state as a result of the collective behavior of particles (second part)

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and the changes of state: melting, boiling, evaporation and condensation (third part). A brief description of all the parts and their items follows:

Part 1: (The particulate nature of matter)

The first 3 items (1A, 1B, and 1C) concern the solid state.

1.A. Pupils are asked to choose among five alternatives (See Appendix), the figure that best represents what they would “see” if they observed a sugar grain using a hypothetical magnifying glass enabling the view of the grain structure.

1.B. Pupils are asked to explain what they think exists between molecules, in case they chose a figure depicting molecules. Otherwise, they do not have to answer this question.

1.C. Pupils are asked to answer whether or not they think that the view of the sugar structure through the hypothetical magnifying glass would remain “frozen” as the time is passing. They are also asked to explain or justify their answers.

The following 3 items (2A, 2B, and 2C) concern the liquid state.

2.A. Pupils are asked to choose among five alternatives (See Appendix), the figure that best represents what they would “see” if they observed a drop of pure (liquid) water using a hypothetical magnifying glass enabling the view of the structure of the drop.

2.B. Pupils are asked to explain what they think exists between molecules, in case they chose a figure depicting molecules. Otherwise, they do not have to answer this question.

2.C. Pupils are asked to answer whether or not they think that the view of the water structure through the hypothetical magnifying glass would remain “frozen” as the time is passing. They are also asked to explain or justify their answers.

The following 3 items (3A, 3B, and 3C) concern the gas state.

3.A. Pupils are asked to choose among five alternatives (See Appendix), the figure that best represents what they would “see” if they observed a very small quantity of oxygen, found inside a vase containing pure oxygen, a hypothetical magnifying glass enabling the view of the structure of the oxygen.

3.B. Pupils are asked to explain what they think that exists between molecules, in case they chose a figure depicting molecules. Otherwise, they do not have to answer this question.

3.C. Pupils are asked to answer whether or not they think that the view of the oxygen structure through the hypothetical magnifying glass would remain “frozen” as the time is passing. They are also asked to explain or justify their answers.

Here, pupils are prompted to circumvent the following items 4 and 5 in case they have not adopted a molecular structure of the substances in the previous items.

Part 2: (The properties of a state as a result of the collective behavior of particles)

The following 3 items (4A, 4B, and 4C) concern the same substance in three different temperatures.

4.A. Pupils are prompted to make the assumption that they have separated one single molecule from one of the following: a block of ice, some pure (liquid) water, or some pure water in the gas state. They are asked whether or not they could understand if the separated molecule has come from ice, liquid water or water in the gas state, respectively. Then, they are also asked to explain or justify their answers.

4.B. Pupils are prompted to make the assumption that they have separated one single molecule from a block of ice, another single molecule from a quantity of pure liquid water and a third single molecule from a quantity of water in the gas state. They are asked whether or not they could determine a physical state for each of the three molecules and if yes, what this state is. Then, they are also asked to justify their answers.

4.C. Pupils are prompted to make the assumption that they have separated one single molecule from a block of ice, another single molecule from a quantity of pure liquid water and a third single molecule from a quantity of water in the gas state. They are asked to compare the shape and the magnitude of the three molecules. Then, they are also asked to justify their answers.

The following 2 items (5A and 5B) concern three different substances under normal (the same) conditions.

Pupils are prompted to make the assumption that they have separated one single molecule from each of the following three substances: sugar (solid), water (liquid) and oxygen (gas).

5.A. They are asked whether or not they could determine a physical state for each one of the three molecules and if yes, what this state is. Then, they are also asked to justify their answers.

5.B. They are asked whether they think that the three molecules are different or not. They are also asked to explain or justify their answers.

Part 3: (The changes of state)

The following 3 items (6A, 6B and 5C) concern melting.

Pupils are prompted to imagine a lump of wax melting on a heating radiator.

6.A. They are asked to identify the substance after melting.

6.B. They are asked to choose among five alternatives (See Appendix), the figure that best represents what they would “see” if they observed wax (a) before melting and (b) after melting, using the hypothetical magnifying glass enabling the view of the structure of the substances.

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6.C. They are asked to explain the way in which the wax melts by taking into account the structure of the matter and describing the procedure in detail.

The following 2 items (7A and 7B) concern boiling.

Pupils are given a figure depicting a beaker of boiling water containing many bubbles. They are asked:

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7.A. To identify the substance that exists at a point: (a) inside a bubble, (b) inside the water between the bubbles and (c) just above the surface of the boiling water.

7.B. To choose among five alternatives (See Appendix), the figure that best represents what they would “see” if they looked at each of the three points of the previous question using the hypothetical magnifying glass enabling the view of the structure of the substances.

The following 3 items (8A, 8B and 8C) concern evaporation.

8.A. Pupils are asked to explain the differences, if any, between boiling and evaporation.

8.B. Pupils are asked to choose among five alternatives (See Appendix), the figure that best represents what they would “see” if they observed evaporated water using the hypothetical magnifying glass enabling the view of the structure of the substances.

8.C. Pupils are asked to explain the way in which the water evaporates by taking into account the structure of the matter and describing the procedure in detail.

The following 2 items (9A and 9B) concern condensation.

Pupils are given the following description: The water in an open saucepan is boiling intensively. We place a cool Pyrex lid above the saucepan and we immediately notice the formation of drops on the down surface of the lid.

9.A. Pupils are asked to identify the substance in the drops.

9.B. Pupils are asked to explain the way in which the drops were formed by taking into account the structure of the matter and describing the procedure in detail.

Before data collection, a small pilot study (N=25) was carried out, followed by interviews with student discussing all items in order to detect possible communication difficulties of the test. A Cronbach’s alpha reliability coefficient of 0.86 was obtained for the above instrument and the present sample.

The marking scheme followed for correct answers was: one point for the items 1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, 3C, 6A, 8B and 9A, two points for the items 4A, 4B, 4C, 5A, 5B, 6B, 6C, 8A and 9B and three points for the items 7A, 7B and 8C. Students, who circumvented items 4 and 5, because they did not adopt the molecular structure, were scored with zero in these items. There were only six students who did not adopt the molecular structure for all

states. The sum of all items constituted students' *total achievement*, which was the main dependent variable of the study, while various parts of the assessing instrument were defined and treated as *independent* variables as well (see next section).

It is worth noticing that pupils' responses to this test were asked without any notification almost one year after pupils had been taught the relevant subject matter. Thus, the test measures the pupils' residual knowledge and that explains the relatively low mean total achievement score (Table 1). The means, standard deviations and Cronbach's internal consistency reliability coefficients for the three cognitive variables as well as the *total achievement* variable are summarized in Table 1.

Table 1 about here

Additional research directions

Apart from students' *total achievement*, some additional dependent variables were introduced. These additional dependent variables express certain aspects or dimensions of the total understanding of the particulate nature of matter and its changes of state and correspond to parts of the assessing instrument. These parts and their corresponding variables are the following: (a) the "particulate part" (part 1). It corresponds to *particulate dimension* and measures pupils' understanding of the particulate nature of matter for each of the three states: solid, liquid and gas state. (b) The "collective part" (part 2). It corresponds to *collective dimension* and measures pupils' understanding of the macroscopic properties of the states as a result of the collective behavior of particles at the microscopic level. (c) The total of the first two parts. It includes both, the "particulate part" and the "collective part"; it measures pupils' total understanding of the structure of matter and corresponds to the dimension *structure understanding*. (d) The third part refers to the changes of state: melting, boiling, evaporation and condensation and corresponds to the dimension *understanding the changes of state*. (e) The combination of the questions 6C, 8A, 8C and 9B measures only pupils' competence in interpreting the changes of states and corresponds to dimension *interpretations*. A comparison between boiling and evaporation (question 8A) is included here, considered as a relative demanding issue that remarkably contributes to clarification of the phenomena.

The effect of the three cognitive variables (FDI, CD and LTh) on the above-introduced additional dependent variables is also investigated. The effects of FDI, CD and LTh on these dependent variables are not expected to be analogous to their effects on the total achievement.

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The various parts of the test measure different dimensions or aspects of understanding, and thus, the cognitive variables might have a different effect on them.

Having defined the new dependent variables, the second hypothesis is reformulated in the following twofold form: *structure understanding*, which includes the *particulate dimension* and the *collective dimension*, along with the three cognitive variables (LTh, FDI, CD) have an effect (1) on students' *understanding the changes of state*, and (2) on *interpretations* as well. A sound understanding of the particulate and collective aspects of the matter can be considered a prerequisite for understanding the changes of state and furthermore for demonstrating competence in interpretation of them, which is something more complicated and demanding. Since the effects of the cognitive variables could be direct on the dependent variables or indirect through the *particulate* and the *collective dimension*, path analyses were implemented to depict such relationships.

Statistical Analysis and Results

Table 2 presents the Pearson correlation coefficients among all the variables used in this study. Noticeably, all of the cognitive variables correlate significantly with all the dependent variables ($p<0.001$). In particular, logical thinking (LTh), field dependence/independence (FDI) and convergence/divergence (CD) correlate significantly with the main dependent variable that is total achievement (0.67, 0.42 and 0.40 respectively, $p<0.001$) as well as with all the other dependent variables: particulate dimension, collective dimension, structure understanding, understanding of the changes of state and interpretations, as the correlation matrix shows.

Table 2 about here

Especially, *interpretations* correlate significantly with the three cognitive variables LTh, FDI and CD (0.49, 0.26 and 0.29 respectively, $p<0.001$) as well as with the particulate dimension and the collective dimension (0.52 and 0.58 respectively, $p<0.001$). The statistically significant correlations among the rest of the dependent variables confirm the high internal consistency among the parts of the whole assessing instrument.

The correlation analysis suggests that merely linear correlation exists between the two variables, when, however, the presence of the others is ignored. Thus, a stepwise linear regression (SLR) was employed in order to provide linear models, which relate the dependent variables with the predictors through stochastic equations (Anderson, 1984). The models

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propose whether a predictor has a statistically significant effect, given that the other variables are present.

In order to determine which cognitive variables have an effect on the dependent variables, given that the other variables are present, six stepwise multiple regression analyses were performed; one stepwise multiple regression analysis for each dependent variable. The results are summarized in Table 3.

Table 3 about here

The first stepwise multiple regression analysis revealed that all of the three cognitive variables: logical thinking, field dependence/independence and convergence/divergence were statistically significant predictors of students' total achievement scores. All of the three predictors together accounted for 48.2% of the total achievement variance. Logical thinking proved to be by far the best predictor accounting for 45.6% of the variance and convergence/divergence and field dependence/independence follow, accounting for 1.6% and 1.0% of the variance respectively. The low percentage of variance explained by FDI and CD as compared to LTh is partially due to the collinearity, since FDI, CD and LTh are correlated. The latter having the stronger effect takes the lion's share of the variance. Note that we deal with a linear model, which captures only the linear components. However, FDI and CD show their importance by the fact that both remain in the model demonstrating a small, but statistically significant linear effect, given that LTh is present.

The second and the sixth stepwise multiple regression analyses indicated that only logical thinking was a statistically significant predictor of students' particulate dimension and interpretation scores. This predictor accounted for 27.9% of the particulate dimension and 23.8% of the interpretations variance respectively.

In the third and fourth stepwise multiple regression analyses, the two out of the three cognitive variables that are logical thinking and field dependence/independence, were determined to be significant predictors of the collective dimension and structure understanding scores. Logical thinking accounted for 27.6% of the collective dimension and 37.7% of the structure understanding variance. Field dependence/independence follows by far, accounting for 1.3% of the collective dimension and 1.0% of the structure understanding variance.

As far as the fifth stepwise multiple regression analyses is concerned, it showed that all of the three cognitive variables that are logical thinking, field dependence/ independence and convergence/divergence were found to be significant predictors of students'

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2 understanding of the changes of state scores. All of the three predictors together accounted for
3 45.2% of the understanding of the changes of state variance. Logical thinking is again by far
4 the best predictor accounting for 41.5% of the variance and convergence/divergence and field
5 dependence/independence are the second and third accounting for 2.9% and 0.8% of the
6 variance respectively.
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10 Three more stepwise multiple regression analyses were applied to determine: (a)
11 which out of five totally variables: the three cognitive (LTh, FDI, CD) as well as the
12 particulate dimension and the collective dimension, have predictive power on the
13 interpretations. (b) Which, out of **four variables**, the three cognitive (LTh, FDI, CD) as well as
14 the particulate dimension have predictive power on collective dimension. (c) Which, out of
15 four totally variables: the three cognitive (LTh, FDI, CD) as well as the *structure*
16 *understanding* have predictive power on students' *understanding the changes of state*. The
17 results are presented in Table 4.
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24 These results show that: (a) only three out of the five variables were statistically
25 significant predictors of students' interpretations scores. The predictors were the following:
26 collective dimension, particulate dimension and logical thinking. All of the three predictors
27 together accounted for 41.9% of the interpretations variance. Collective dimension was
28 proved to be by far the best predictor accounting for 32.7% of the variance and particulate
29 dimension and logical thinking follow, accounting for 7.6% and 1.6% of the variance
30 respectively. (b) Only logical thinking and particulate dimension were statistically significant
31 predictors of students' collective dimension scores. Logical thinking was the best predictor
32 accounting for 26.5% of the variance and the particulate dimension follows, accounting for
33 5.7% of the variance. (c) *Structure understanding*, logical thinking and convergent/divergent
34 cognitive style were statistically significant predictors of students' *understanding the changes*
35 *of state*. The three predictors accounted for 53.8% and 5.8% and 1.7% of the variance
36 respectively.
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43 Following, path analyses were employed, where the standardized regression betas of
44 the corresponding regression equations were used as path coefficients (Bryman & Cramer,
45 1990).
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48 Path I diagram (Figure 1) shows that logical thinking had a significant direct effect
49 (0.25) on *Understanding the changes of state* and an indirect effect via *Structure*
50 *understanding* ($0.56 \times 0.53 = 0.30$). LTh has a total effect of 0.55 ($0.25 + 0.30$). FDI has an
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indirect effect via *Structure understanding* ($0.13 \times 0.53 = 0.07$) and CD has a direct effect of 0.15. The total causal effect was 0.77 calculated as the sum of the direct and indirect effects.

Path II diagram (Figure 2) shows that logical thinking had a significant direct effect (0.17) and also three indirect effects on *interpretations*: (1) via *particulate dimension* ($0.53 \times 0.26 = 0.14$), (2) via *collective dimension* ($0.36 \times 0.36 = 0.13$) and (3) via both *particulate* and *collective dimension* ($0.53 \times 0.29 \times 0.36 = 0.06$). A total causal effect of 0.50 was calculated.

Figure 1 and 2 about here

Interpretation of results and Discussion

In this section an attempt is made for a theoretical interpretation of the results that came out from the statistical analysis. That is, to relate some aspects of the cognitive skills that are behind the psychometric measurements to the nature of mental tasks involved when learning this specific domain material.

Results from SLR on total achievement (Table 3) supported the main hypothesis of this study, that all of the three cognitive variables (LTh, FDI and CD) affect students' performance. Out of the three cognitive predictors, logical thinking ability (LTh) was by far the best, accounting for the lion's share of the total achievement score variance and it appears to have an effect on every other dependent variable. Noticeably, it was the only significant predictor of 'particulate dimension' and 'interpretations' (Table 3). These results are consistent with other findings in previous studies that reported the supremacy of logical thinking as a predictor variable on science achievement (Chandran et al. 1987; Lawson & Thomson 1988; Johnson & Lawson 1998; Kang et al., 2005;). Lawson (1985) concluded that "deficiencies in formal reasoning are a probable cause of achievement deficiencies in the sciences, mathematics etc". Correspondingly, the results of this study support the hypothesis that an adequate level of logical thinking appears to be necessary for students to understand the particulate nature of matter and its changes of state.

CD cognitive style was also a significant predictor of the students' total achievement scores (Table 3). It appears that divergent pupils were favored in understanding the particulate nature of matter and its physical changes. This might seem contradicting at first sight, with research reports stating that those who mostly show aptitude for science are convergers (Hudson 1966). However, a closer look on the learning material explains this inconsistency. The mental tasks involved in learning this domain of early science that includes the

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particulate nature and the changes of state of matter, are not analogous to those of demanding problems that need unique solutions clearly obtainable from the information available, which would favor convergent thinkers (Child & Smithers, 1973).

On the other hand, the content of scientific material that the assessing instrument covered in this study involves a diversity of concepts, properties and models, which mostly require detailed descriptions in order to be understood when studied or taught. Therefore, it is reasonable to assume that linguistic skills may have played a major role in students' understanding of the relevant scientific topics. Linguistic skills, such as comprehension and interpreting of a scientific text, are considered to be of paramount importance for reasoning in science (Byrne et al. 1994). Students, though, who show superiority in language, are thought to be divergent thinkers (Hudson, 1966; Runco, 1986; Danili & Reid, 2006). Links between divergency and science has also been reported in the literature. As it was mentioned in a previous section of this study, Hudson (1966) noted that the convergers tended to choose the sciences, but the divergers who did choose the sciences performed very well. Following, other research findings were consistent with Hudson's claim (Al-Naeme, 1991; Field & Poole, 1970).

Based on the degree of linguistic skills required in a mental task, one could explain why CD cognitive style had an effect on some variables, such as 'total achievement' and 'understanding the changes of state', while it had no effect on some others. CD had no effect on 'Particulate dimension', 'collective dimension', and 'structure understanding' because teaching and studying of the corresponding themes can be assisted by simple illustrations and no extended additional descriptions are required, so that the role of language here does not seem to be determinative. While the effect of CD is favored when the content requires linguistic ability, a limit should exist determined by the complexity of the task. When the task becomes more complex and requires logical operations leading to a conclusion or a unique final answer, then other abilities, such as formal reasoning and even convergent thinking, might prevail and the effect of divergency becomes less significant. Such appear to be the 'interpretations' variable case.

Field dependent/independent (FDI) cognitive style was the third significant predictor of students' total achievement scores (Table 3). Field independent students were those who performed better. This result is consistent with other findings in previous studies, which showed that field independence is an intellectual asset concerning general achievement in science (Lawson, 1983; Johnstone & Al-Naeme, 1995; Niaz, 1996; Tinajero & Paramo, 1998; Bahar & Hansell, 2000; Danili & Reid, 2004; Kang et al., 2005; Tsaparlis, 2005; Author 2 et

al., 2005; Danili & Reid, 2006). It can be inferred that field independent pupils' ability to separate readily the significant information from its context (Witkin & Goodenough, 1981) or the *signal* from the *noise* offered them a serious advantage, either in their study or during teaching.

Field dependence/independence (FDI) had also an effect on the most of the dependent variables that measured certain aspects or dimensions of the total understanding of the particulate nature of matter and its changes of state. These are the following: 'collective dimension', 'structure understanding' and 'understanding of the changes of state'. All the above involve a complex context, that might be misleading for students' thought, and thus the field independent style has an advantage. On the contrary, FDI had no effect on 'particulate dimension' and 'interpretations'. The former referred to three specific models, one for each physical state, that are well described by the corresponding figures, so that no room for misleading information is left and thus, no effect of FDI is observed. Nevertheless, when the same models are asked to be recognized by the students, within a more complex and possibly misleading context, e.g. in 'understanding of the changes of state', FDI appears again to be a predictor (Table 3, model 5).

For the 'interpretations' case, however, the explanation is different and analogous to the one for CD. Interpretation of phenomena requires a deeper understanding and reasoning skills, so that logical thinking (LTh) prevails among all possible predictors, as the SLR confirms it (Table 3, model 6).

The dimensions 'collective' and 'particulate' are affected by cognitive variables and in addition, when treated as independent variables combined with the cognitive variables are shown to have an effect on students' performance in understanding the changes of state and interpretations of these physical phenomena. These effects, direct and indirect, which are shown in the path analyses (Figures 1 & 2), provide support for the second hypothesis of this study. They indicate that 'collective' and 'particulate' dimensions of students' understanding of this subject matter constitute fundamental and substantial presuppositions for interpreting the phenomena of the changes of state. Similar findings have been also reported in relevant qualitative (Johnson, 1998c) and quantitative studies (Author 3, Author 2 et al., 2008). As it was mentioned in the introduction section, Johnson (1998c) concluded that understanding of the nature of the gas state was "the underlying issue" for the understanding of the state changes "with the particle theory playing a key role". Interestingly, 'interpretations' variable was also affected directly by LTh, which underlines the importance of formal reasoning in the related cognitive processes. On top, when a deeper knowledge on changes of physical states is

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pursued, being familiar merely with the particulate models of two physical states, pre and post the change, is not adequate. There is also a dire need for understanding the transition from one model to the other, where reasoning abilities are thought to be of great importance. This is consistent with the direct effect of logical thinking on interpretations. In the main, logical thinking appears to be the bottom line for competence in ‘interpretations’, since the former, as the path analysis shows, has a direct effect on the latter and indirect effects as well, via particulate and collective dimensions. The effect of ‘particulate dimension’ on ‘collective dimension’, shown in the path analysis II, could be explained by the fact that understanding particulate models are thought to precede understanding collective properties and the former to be a presupposition for the latter.

Concluding, it is important to state that the hypotheses are well supported by the data. It is very important, that up to 48,2% of the students’ achievement variance was explained and all the related model-parameters were statistically significant. Thus, we maintain that the findings of the present research are of paramount importance, because they shed light on the factors hindering students’ understanding of the particulate nature of matter and the changes of states. On the other hand, the present study opens a new area of investigations for the conceptual change in this particular domain, where the individual differences, such as logical thinking and cognitive styles, have been ignored from research hypotheses.

Implications for teaching

There are four implications of the present findings for the practice of science education. The first concerns students’ insufficiency in formal reasoning, which was found to be the main origin of their difficulties. In order to assist students lacking formal operational abilities, teachers are required to utilize such teaching methods that make abstract concepts more accessible through concrete-operational thought. These methods make use of illustrations, diagrams and models that constitute perceptible entities or concrete materials to focus attention on critical and variable attributes of abstract concepts. There is evidence that these methods can enhance the attainment of abstract concepts (Cantu & Herron, 1978; Howe & Durr, 1982; Zeitoun, 1984). Another alternative for dealing with the problem is to design training programmes that promote development in students’ formal operational reasoning (Lawson, 1985).

The second implication concerns students’ field dependent/independent ability. Although the field-independent ability may be developed naturally with experience, it is

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2 difficult to teach someone to be field independent. However, effort should be made during
3 teaching in order to help students making sense of the material taught, when attending lessons
4 in classroom or reading their school textbooks, by focusing on central ideas and disembedding
5 only the relevant information.
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8 The third implication is related to convergent/divergent thinking. According to the
9 findings of this investigation, in this early science domain, lack of diverging thinking seemed
10 to be a disadvantage due to the restricted linguistic skills. Since short-term progress in these
11 linguistic skills is not likely to be achieved, the assistance to students could be given by
12 methods that present and develop the teaching material by circumventing the dominating role
13 of language as much as possible. That is, by methods which implement illustrations and
14 diagrams that clarify the particulate structures of substances in the three physical states, and
15 software simulations that demonstrate the transition from one state model to another.
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20 Finally, the fourth implication concerns the background role of the particulate and the
21 collective dimensions of students' understanding of the nature of matter. Teaching should
22 primarily and intensively focus attention on these two dimensions considering them as the
23 underlying issue for the understanding the changes of state.
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Appendix- Figure 3 about here

For Peer Review Only

Table 1. Descriptive statistics for the tests

Variable	Maximum score possible	N	Mean	Standard Deviation	Cronbach's alpha
FDI	20	309	6.21	4.15	0.84
CD	100	298	43.10	11.31	0.76
LTh	60	310	19.47	10.64	0.79
Total Achievement	39	300	7.77	6.55	0.86

Table 2. Correlation matrix

Variable Number and Name	1	2	3	4	5	6	7	8	9
<u>Dependent Variables</u>									
1. Total Achievement	1,00								
2. Particulate dimension	0,80*	1,00							
3. Collective dimension	0,80*	0,48*	1,00						
4. Structure Understanding	0,93*	0,85*	0,87*	1,00					
5. Understanding the Changes of State	0,93*	0,64*	0,61*	0,73*	1,00				
6. Interpretations	0,75*	0,52*	0,58*	0,64*	0,76*	1,00			
<u>Predictors</u>									
7. LTh	0,67*	0,53*	0,52*	0,61*	0,64*	0,49*	1,00		
8. FDI	0,42*	0,29*	0,35*	0,37*	0,40*	0,26*	0,46*	1,00	
9. CD	0,40*	0,24*	0,31*	0,32*	0,42*	0,29*	0,42*	0,35*	1,00

* $p < 0.001$

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Table 3. Adjusted R^2 , Percentage of Variance explained, Regression Slopes, Standard Errors, Beta standardized coefficients, t -tests and Model Fit for various models.

Model		Adj R^2	% of Variance Explained	b	seb	Beta	t	F
1. Total achievement (Dependent Variable)		0.482	48.2					79.6***
Predictors	LTh		45.6	0.343	0.032	0.568	10.60***	
	CD		1.6	0.075	0.030	0.127	2.52*	
	FDI		1.0	0.190	0.081	0.122	2.35*	
2. Particulate dimension (Dependent Variable)		0.279	27.9					
Predictor	LTh		27.9	0.097	0.009	0.531	10.61***	112.6***
3. Collective dimension (Dependent Variable)		0.289	28.9					56.4***
Predictors	LTh		27.6	0.094	0.012	0.462	7.96***	
	FDI		1.3	0.073	0.030	0.139	2.40*	
4. Structure Understanding (Dependent Variable)		0.387	38.7					87.1***
Predictors	LTh		37.7	0.183	0.018	0.556	10.32***	
	FDI		1.0	0.107	0.046	0.126	2.34*	
5. Understanding the changes of state (Dependent Variable)		0.452	45.2					70.9***
Predictors	LTh		41.5	0.169	0.018	0.521	9.46***	
	CD		2.9	0.055	0.016	0.175	3.37**	
	FDI		0.8	0.096	0.045	0.114	2.14*	
6. Interpretations (Dependent Variable)		0.238	23.8					91.2***
Predictor	LTh		23.8	0.051	0.005	0.491	9.55***	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4. Regression slopes, standard errors, *t*-tests, beta standardized coefficients, adjusted R^2 , percentage of variance explained and model fit for predicting of performance on *Interpretations*, *Collective Dimension* and *Understanding the changes of state*.

Model		Adj R^2	% of Variance Explained	b	seb	Standardized Beta	t	F
1. Interpretations (Dependent Variable)		0.419	41.9					70.1***
Predictors	Collective dimension		32.7	0.189	0.028	0.364	6.64***	
	Particulate dimension		7.6	0.148	0.032	0.258	4.67***	
	LTh		1.6	0.017	0.006	0.166	2.93**	
Excluded: FDI, CD								
2. Collective Dimension (Dependent Variable)		0.322	32.2					69.5***
Predictors	LTh		26.5	0.073	0.012	0.364	6.37***	
	Particulate dimension		5.7	0.318	0.063	0.288	5.03***	
Excluded: FDI, CD								
3. Understanding the Changes of State (Dependent Variable)		0.613	61.3					143.2***
Predictors	Structure understanding		53.8	0.529	0.048	0.532	11.13***	
	LTh		5.8	0.082	0.016	0.254	5.09***	
	CD		1.7	0.048	0.013	0.150	3.57***	
Excluded: FDI								

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

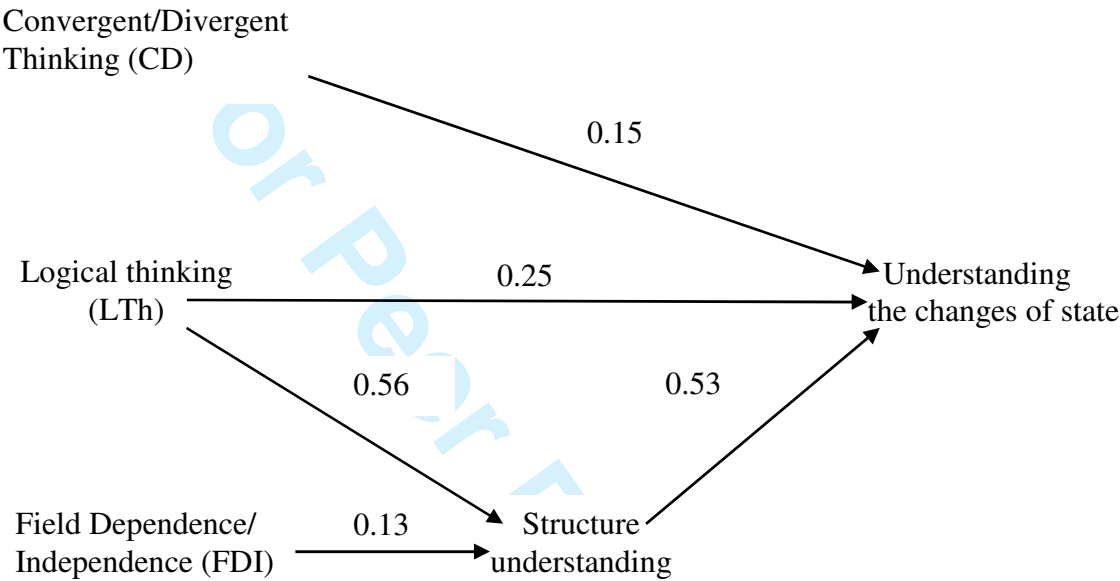


Figure 1. A path analysis for hypothesized relationships between the three cognitive variables: Logical thinking (LTh), Convergent/Divergent Thinking (CD), Field Dependence/Independence (FDI), ‘Structure understanding’ and students’ understanding the changes of state. The total causal effect is 0.77.

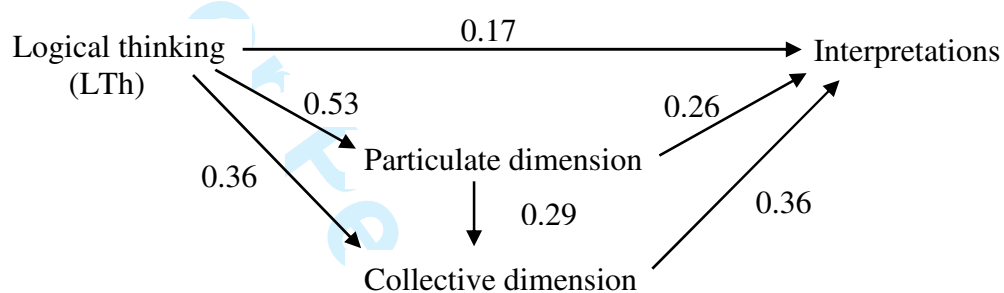


Figure 2. A path analysis for hypothesized relationships between students' competence in interpretation of the changes of state, logical thinking (LTh) and particulate and collective dimensions of students' understanding of the nature of matter. The total effect is 0.50.

APPENDIX

Figure 3. Figures included in the test as stimuli.

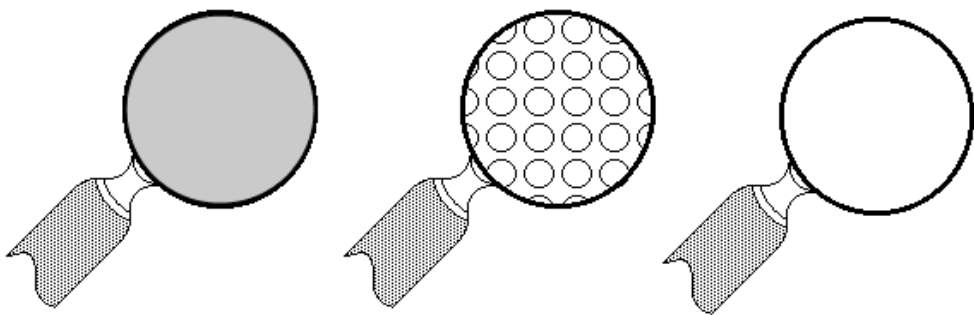


Figure 1:
Continuous substance

Figure 2:
Molecules (be it of nearly spherical shape)
which are in array, not touching each other

Figure 3:
Nothing

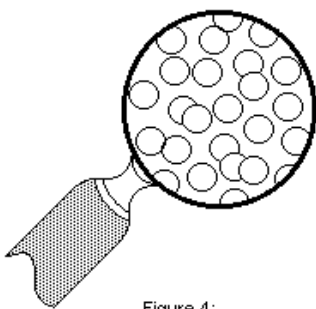


Figure 4:
Molecules (be it of nearly spherical shape)
which are in random positions relatively close
to each other, not touching each other.

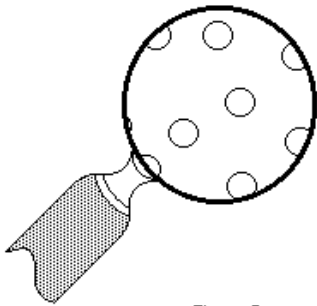


Figure 5:
Molecules (be it of nearly spherical shape)
which are in random positions, mostly far
away from each other.